Colliding-wind binaries

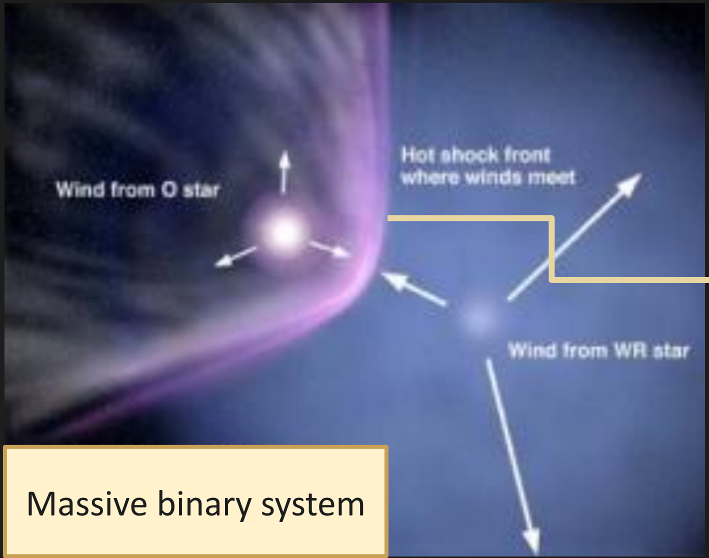
Santiago del Palacio
Chalmers University of Technology

PANTERA Stars

CHALMERS UNIVERSITY OF TECHNOLOGY

VGRSS VI - 2023

Colliding-wind binaries



Massive binary system

Wind collision region

$\dot{M} \sim 10^{-6}\ \mathrm{M_\odot\ yr^{-1}}$

$v_\infty \sim 1000\,\mathrm{km\,s^{-1}}$

⇓

$P_{\mathrm{kin}} \sim 10^{36}\ \mathrm{erg\,s^{-1}}$

$E \sim 10^{50}\ \mathrm{erg}$

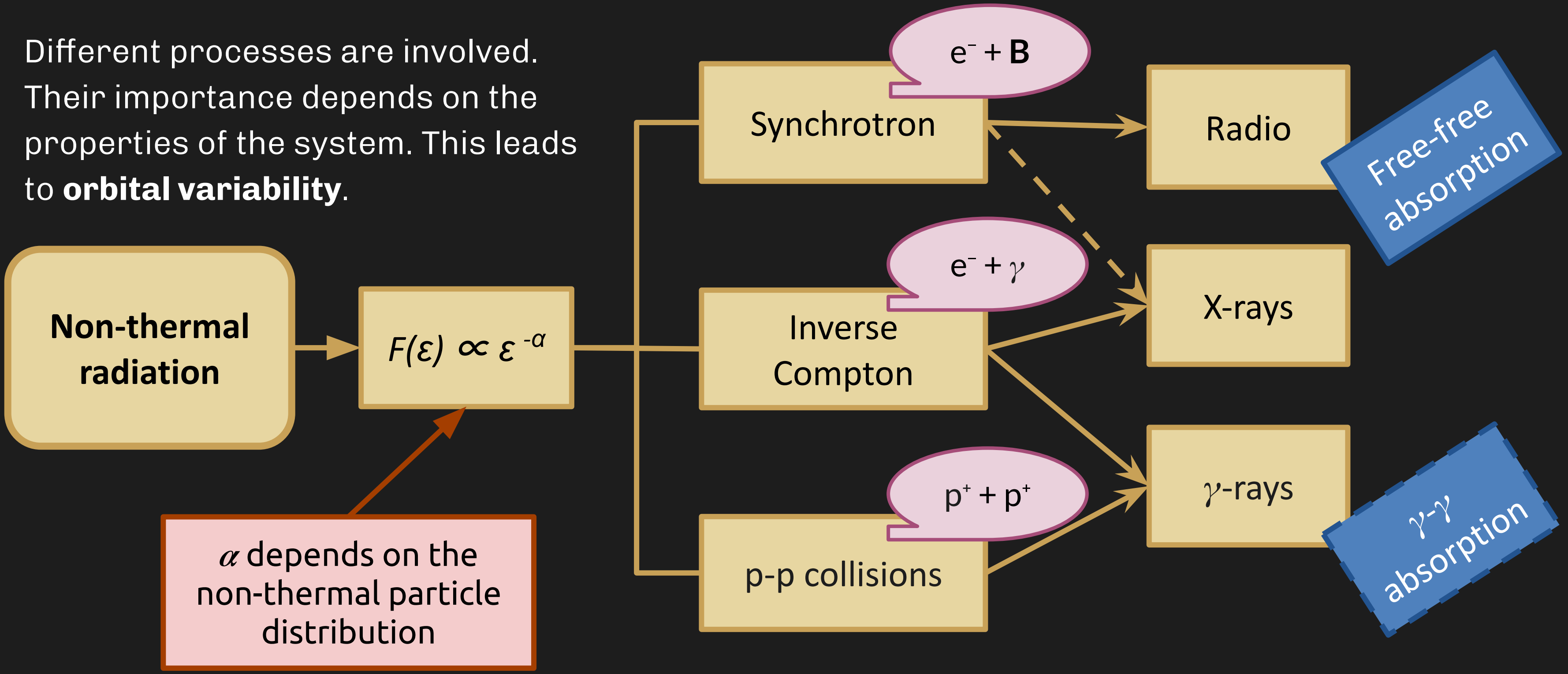
Kinetic to internal energy

Thermal emission → "Soft" X-R (ε < 10 keV)

Non-thermal emission → Radio (cm), hard X-R, γ-R

Non-thermal emission

Different processes are involved. Their importance depends on the properties of the system. This leads to **orbital variability**.

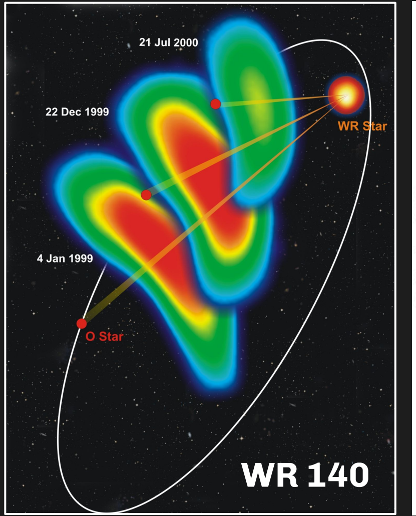


Observational status

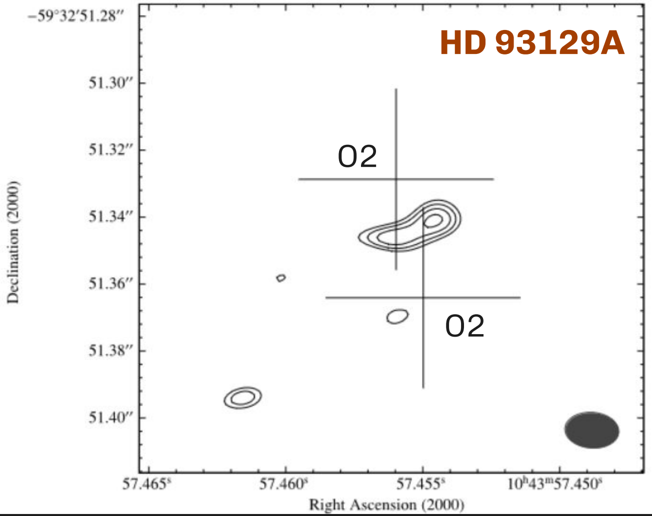
- **+40 CWBs identified in radio**

  Synchrotron emission, variability, or resolved wind-collision region → ~wide orbits

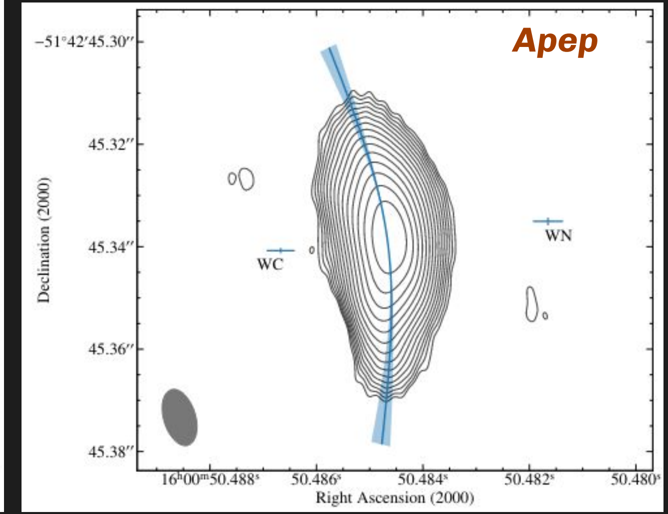
Dougherty+ 2005



Benaglia+ 2015

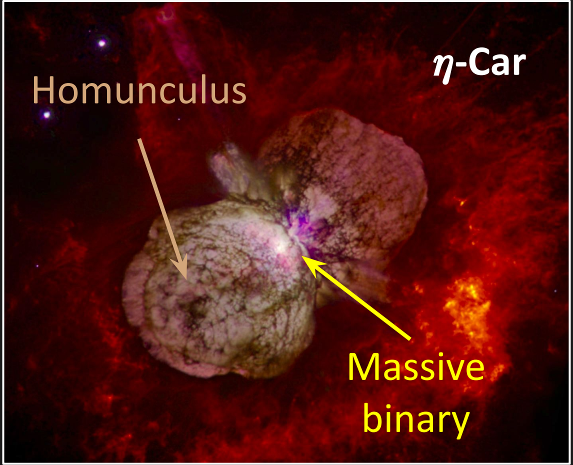


Marcote+ 2021

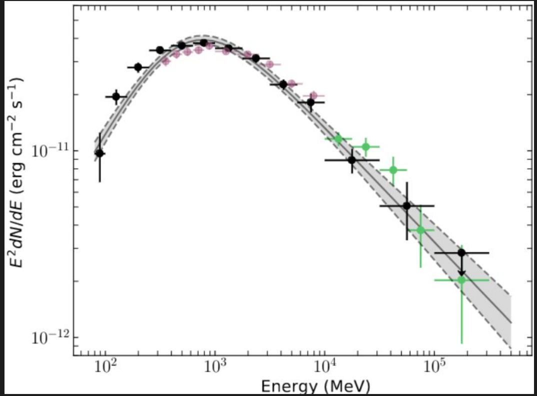


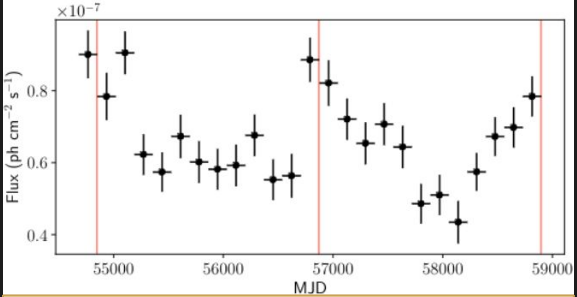
Observational status

- **+40 CWBs identified in radio**
- **2 CWBs detected in γ-rays**
  Orbital variability, power-law spectra, most likely p-p emission $\longrightarrow$ Powerful winds, ~compact systems (self-absorbed radio emission).



Detected with *Fermi* (Tavani+09) and H.E.S.S. (HESS Coll.+20)





Fermi SED and 100 MeV - 10 GeV lightcurve (Marti-Devesa+21)

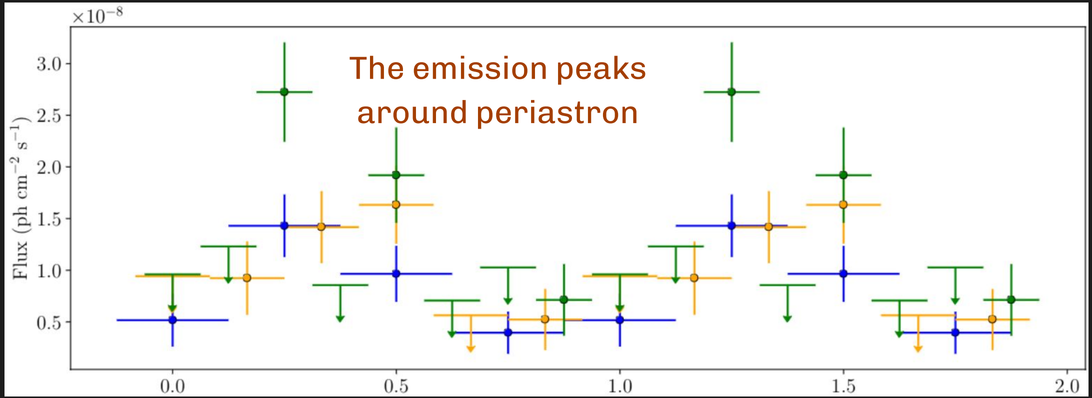
Observational status

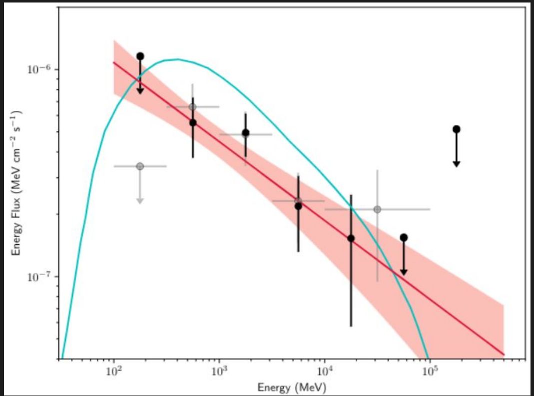
- **+40 CWBs identified in radio**
- **2 CWBs detected in γ-rays**

  Orbital variability, power-law spectra, most likely p-p emission $\longrightarrow$ Powerful winds, ~compact systems (self-absorbed radio emission).

No CWB has been detected both in radio and γ-rays

γ^2-Velorum was detected with *Fermi* (Pshirkov+16, confirmed by Martí-Devesa+20)



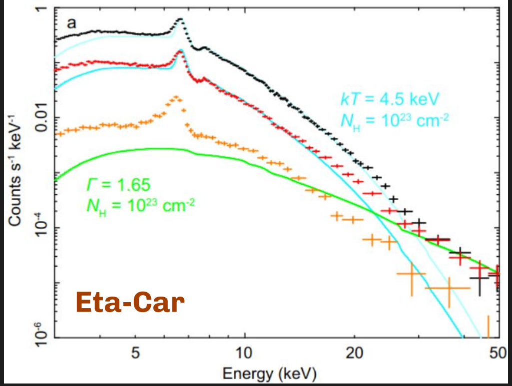


Observational status

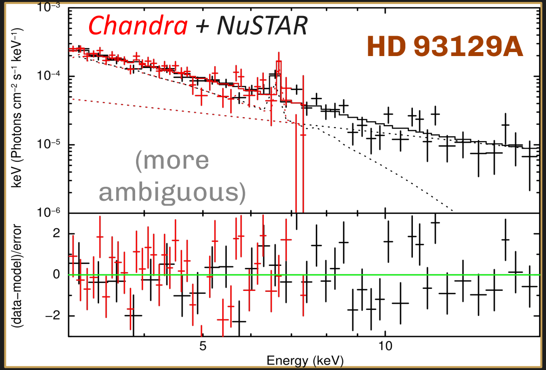
- **+40 CWBs identified in radio**
- **2 CWBs detected in γ-rays**
- **2 (3?) CWBs detected in hard X-rays**

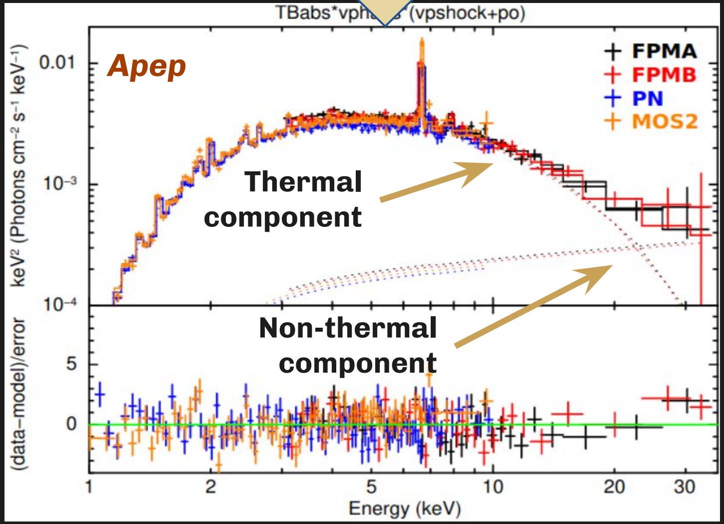
Apep **is the first system detected at radio and at high-energies!**

Hamaguchi+18



del Palacio+20





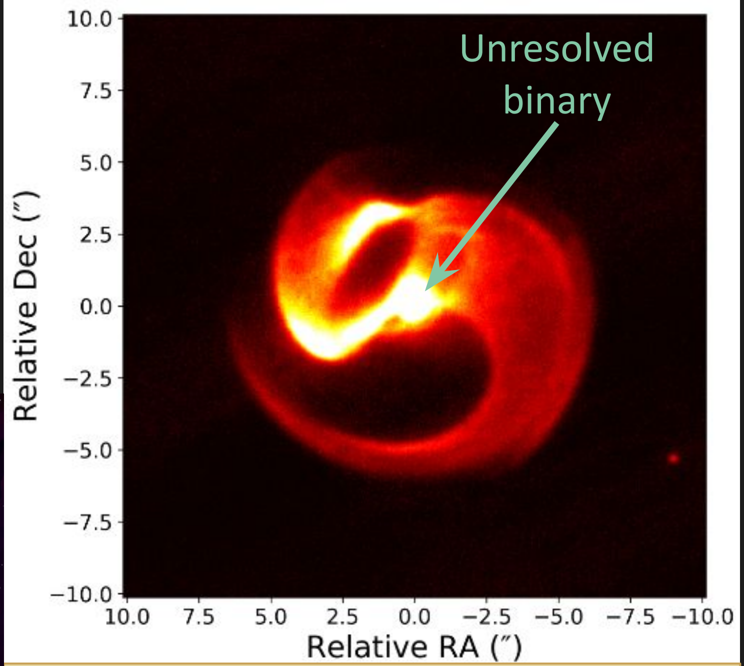
del Palacio+23

The system Apep

- Recently discovered, d ~2.4 kpc. Peculiar case of a WR binary (WN + WC) (Callingham+19).
- It presents extended IR emission produced by a dust plume (Callingham+19, Han+20).
- The stars have very powerful winds:

  v_∞≃3500 and 2100 km/s

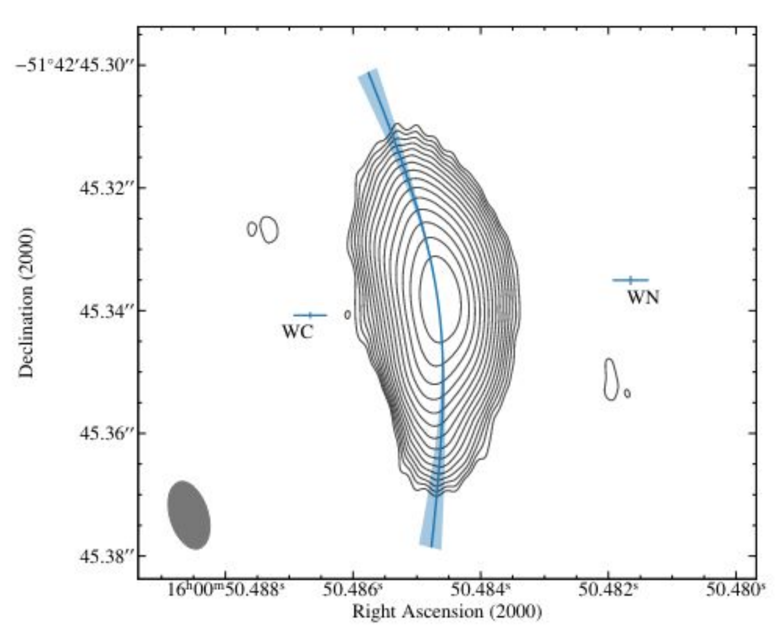
  mass-loss rates of ~10^{-5} $M_\odot$/yr (Callingham+20).



Emission in J band (1.3 μm) observed with the VLT (Han+2020)

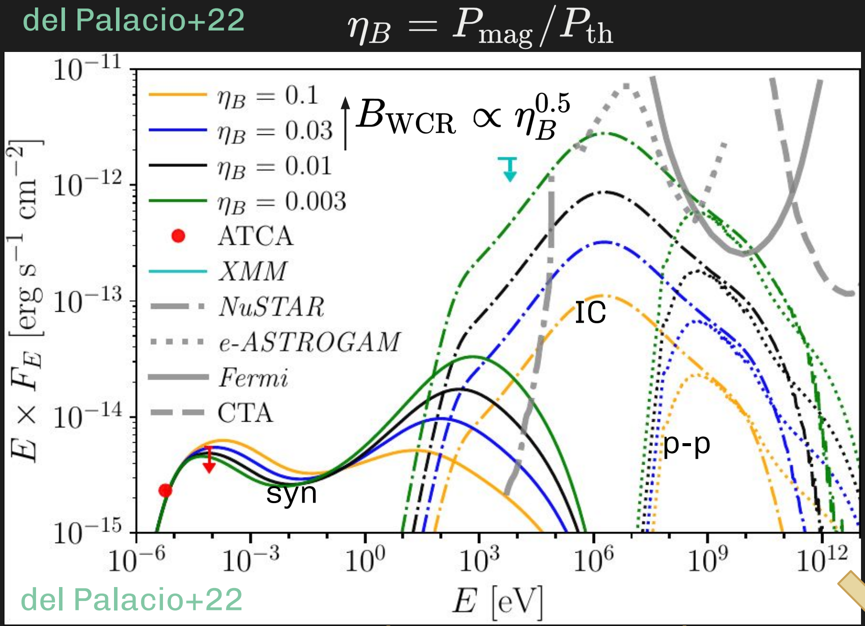
The system Apep

- This is the most **powerful synchrotron-emitter** CWB: $S_{1.4\ \mathrm{GHz}}$ = 166 mJy. Spectral index α=-0.71 (Callingham+19).
- The stars are separated by 47 mas (D_{proj} = 113 AU).
- $\eta = \frac{\dot{M}_1 v_{\infty,1}}{\dot{M}_2 v_{\infty,2}} = 0.44 \pm 0.08$ (Marcote+21)
- The SED shows a spectral break at ν < 1 GHz (Bloot+21).
- Bright X-ray source (Callingham+19, del Palacio+23).



Wind collision region resolved with VLBI at 1.4 GHz (Marcote+2021)

Previous Results



del Palacio+22

The electron population that produces the synchrotron emission also produces IC emission. The p-p emission is poorly constrained.

Using our **non-thermal emission model** we could:

- Constrain the magnetic field intensity and the fraction of the available wind kinetic power converted to non-thermal electrons ($f_{NT,e}$)

$$B_{WCR} \sim 70 - 400 \text{ mG}$$

$$f_{NT,e} \approx (0.1 - 2.7) \times 10^{-3}$$

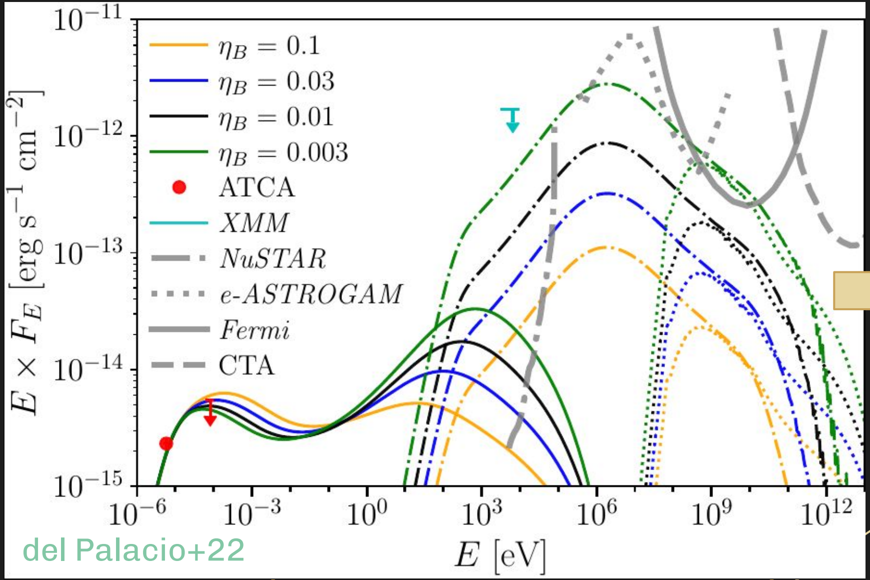
Degeneracy cannot be solved with radio data alone

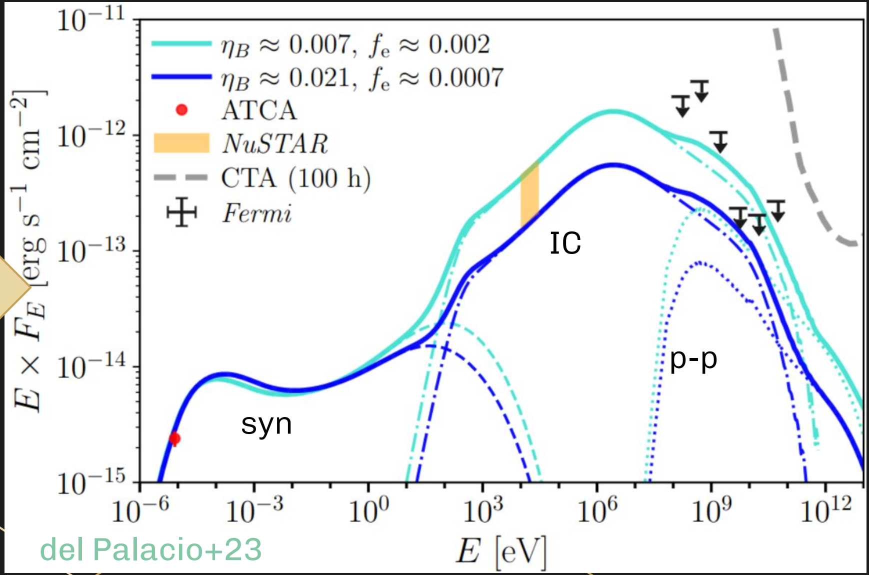
- Predict the hard X-ray and γ-ray flux (though with a huge uncertainty)

Higher B = less emission at high energies

New results

We now have much stronger constraints in the SED thanks to the *NuSTAR* detection (del Palacio+23) and the ULs from *Fermi* (Martí-Devesa+23)

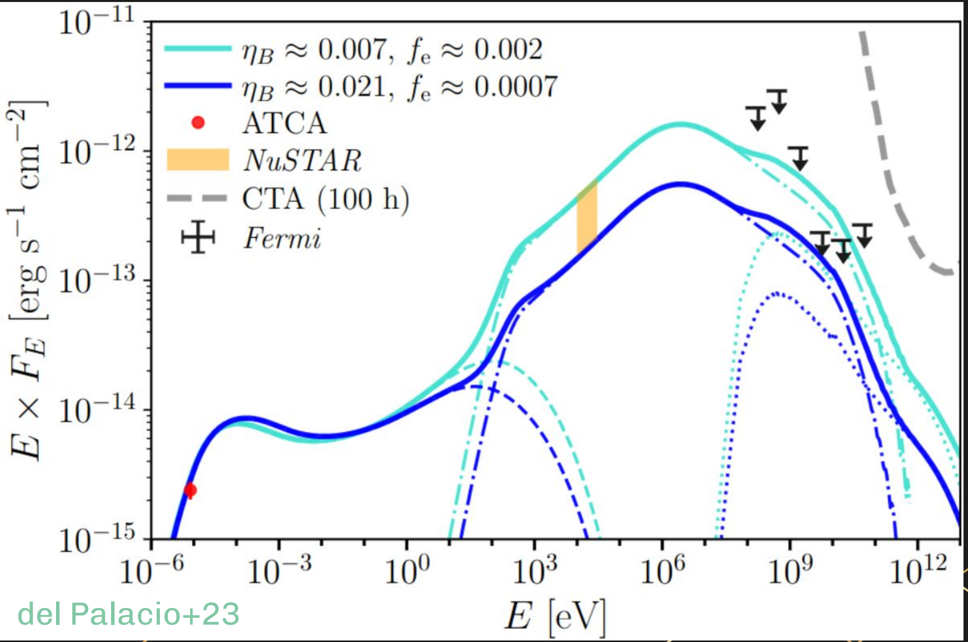




New results

We fitted the SED with the new constraints from *NuSTAR* →

$$B_{\rm WCR} = 105 - 190\ {\rm mG}$$
$$\eta_B = 0.007 - 0.021$$
$$f_{\rm NT,e} \approx (0.7 - 2.1) \times 10^{-3}$$



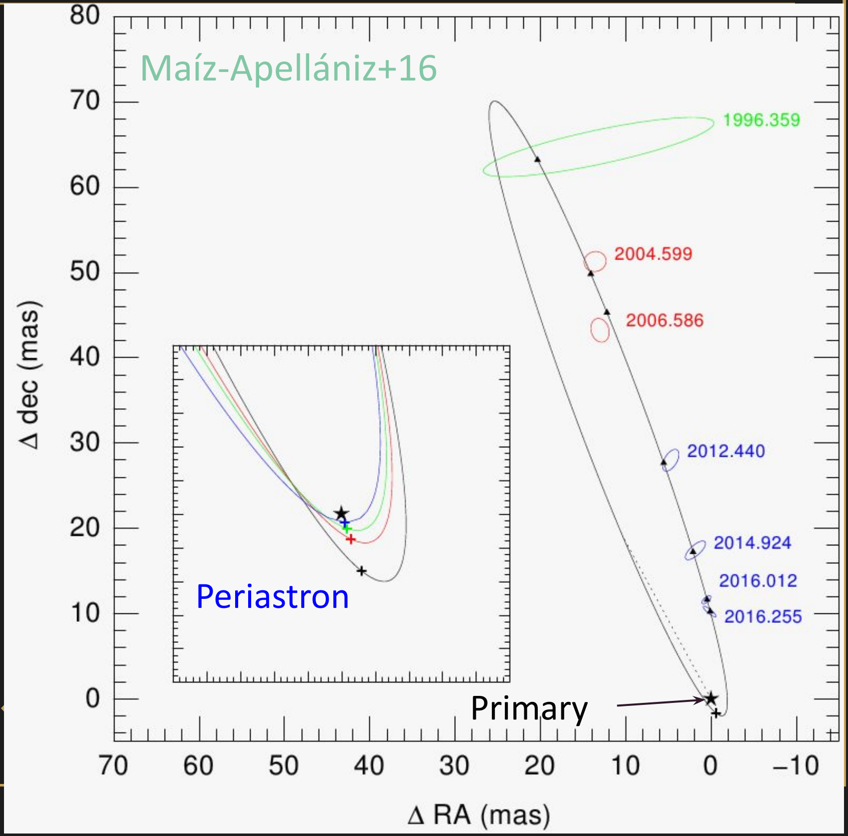
We reduced the uncertainties in the magnetic field intensity and $f_{\rm NT,e}$ from >1 dex to **within a factor ~3.**

~1.5x10^{-4} of the total wind kinetic power is transferred to relativistic electrons

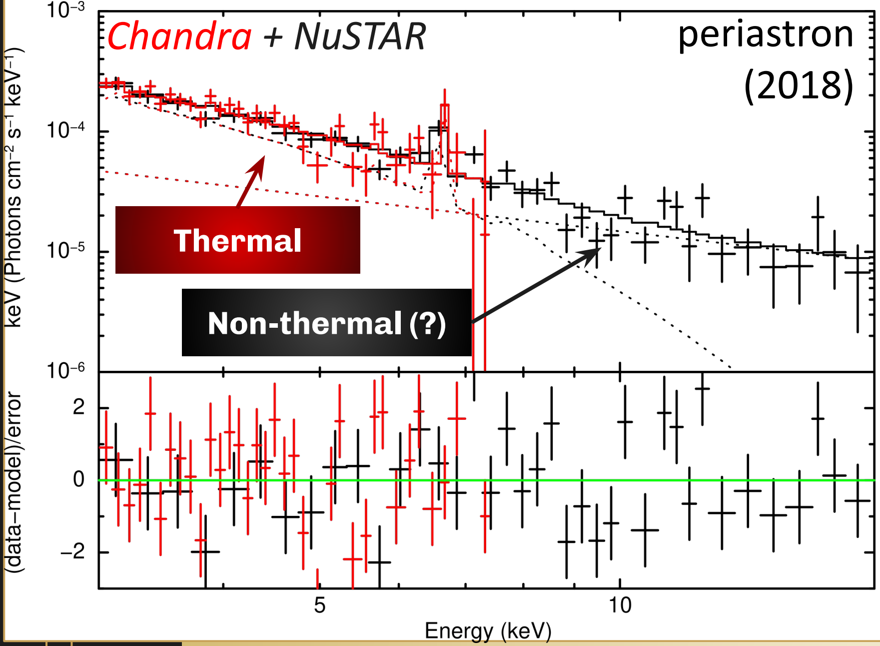
The value of $B_{\rm WCR}$ requires either stellar magnetic fields of ~300-1100 G or **magnetic field amplification** at the shocks

The system HD 93129A

- ★ HD 93129A is one of the most extreme and massive CWBs in our Galaxy (O2 + O2).
- ★ Long period orbit: $P \sim 100$ yr, $a_p \sim 10$ AU.
- ★ Non-thermal emission from the wind-collision region resolved in radio (Benaglia+15).
- ★ Possible non-thermal source at high energies (hard X-rays/γ-rays)

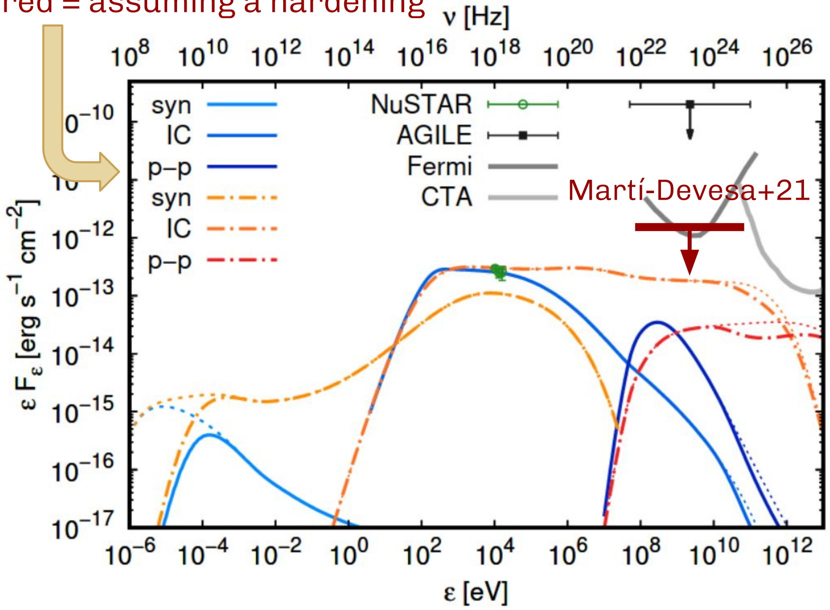


The system HD 93129A



blue = soft spectrum (radio)
red = assuming a hardening

del Palacio+20



The 2018 X-ray observations allowed us to constrain B_{WCR} and $f_{NT,e}$

→ we estimated $f_{NT,e}$ ~ 0.6% and B_{WCR} ~ 0.5 G <u>(with very large uncertainties)</u>

Conclusions

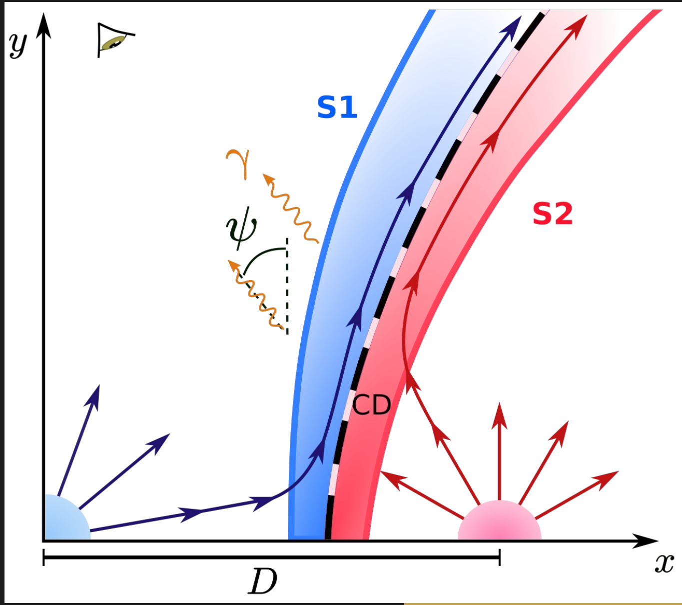
- **CWBs are faint high-energy sources**, with very few detections.
- **Radio observations are insufficient** to characterise the non-thermal particle population. Potentially, great **synergy with observations at high-energies** (X-rays and γ-rays). However, bright in radio $\not\leftrightarrow$ bright in γ-rays.
- Multi-wavelength observations + detailed **modelling** can shed light on the **properties of CWBs** (magnetic fields, particle-acceleration efficiency).
- We now have one system (*Apep*) that might be used as a benchmark for CWBs!

Thank you

Extended emitter model

1. Wind-collision region = axisymmetric surface.
2. Adiabatic shock + laminar flow (x2).
   Semi-analytical prescriptions of the shocked fluid.
3. Relativistic particles accelerated at the shocks as $Q(E) \propto E^{-p}$, with *p* given by radio observations.
4. Compute the non-thermal emission (sync., IC, p-p) and absorption processes (FFA, R-T, γ-γ).
5. Free parameters: magnetic field intensity (*B*) and fraction of energy injected in relativistic particles (f_{NT}).

del Palacio+2016



Transport equation

Stationary and inhomogeneous structure made up of multiple 1-D emitters

For a given 1-D linear emitter we obtain *N(E)* at each position:

- First cell ($j = i_{min}$):

$$N_0(E, i_{\rm min}) \approx Q(E, i_{\rm min})\, \min(t_{\rm cell}, t_{\rm cool})$$

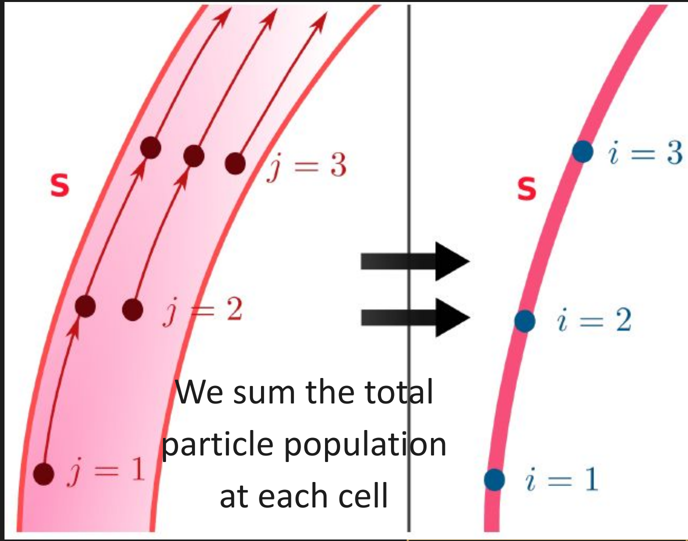
$$L_{\rm NT}(i_{\rm min}) = f_{\rm NT} L_{\rm w,\perp}(i_{\rm min})$$

- Next cells ($j > i_{min}$):

$$N(E', i+1) = N(E, i) \frac{|\dot{E}(E, i+1)|}{|\dot{E}(E', i+1)|} \frac{t_{\rm cell}(i+1)}{t_{\rm cell}(i)}$$

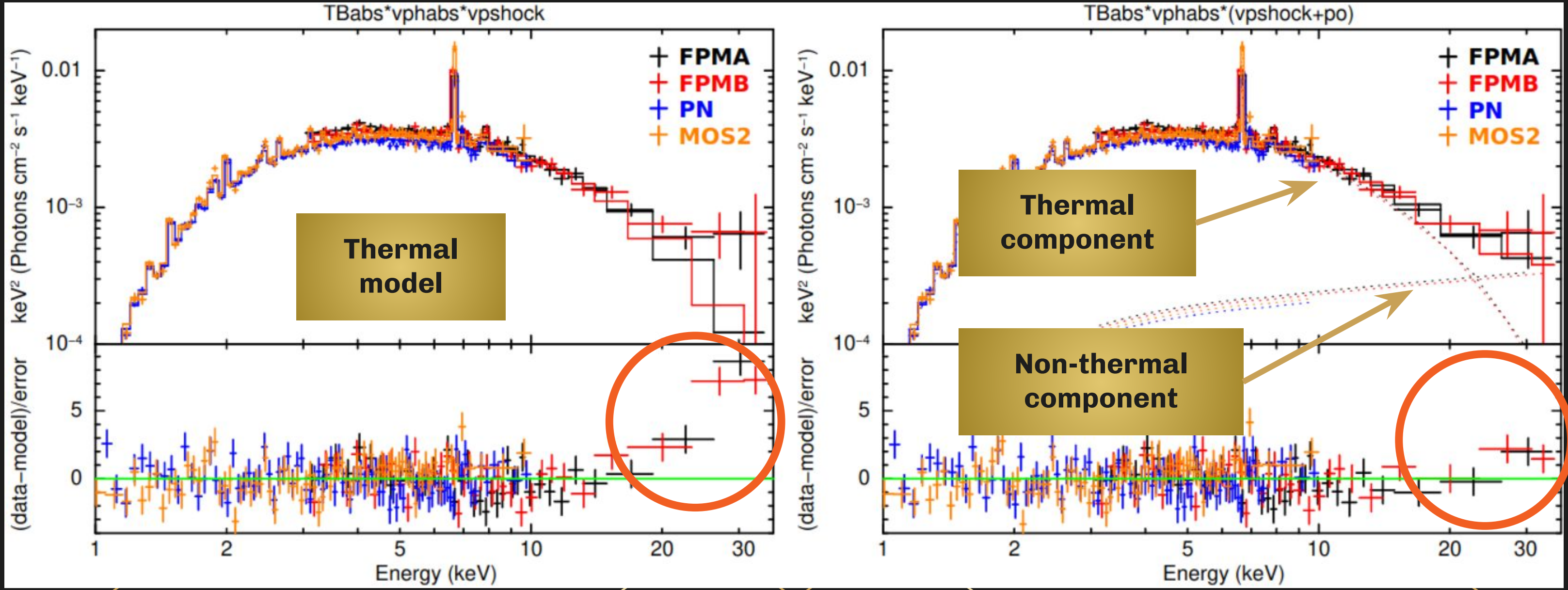
del Palacio+22

del Palacio+16



Apep observations

- We got 60 ks of observations with *NuSTAR* (the only X-ray satellite with imaging capabilities in the > 10 keV energy range) + archival *XMM-Newton* observation (0.3-10 keV energy range).
- We found a power-law component with a flux of $F_{10-30\,\mathrm{keV}} = (4.2 \pm 1.2) \times 10^{-13}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$



del Palacio+ 2023